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Inelastic Neutron Cross Sections on Nuclei at FNAL*

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Direct experimental measurements of the inelastic cross sections of neutrons on a variety of nuclei have been made at Fermilab over the energy range from 50 to 350 GeV. These data may be used, together with nucleon-nucleon total cross sections measured through the same energy range, to justify and verify the interpretation of cosmic ray data on interaction mean free paths in air or iron in terms of nucleon-nucleon total cross sections at much higher energies.

1. Introduction A neutron beam has been used to measure inelastic neutron-nucleus cross sections over the energy range 50-350 GeV at the Fermi National Accelerator Laboratory.

The nuclear mean free path, i.e. the inelastic nucleon-nucleus cross section, in various meterials, is a fundamental parameter in air shower and calorimeter calculations, and the energy dependence of this quantity is used to infer the behaviour of the nucleon-nucleon total cross sections from cosmic ray data at energies inaccessible to existing accelerators (Yodh, 1972, Gaisser, 1975). However, in spite of good data on nucleon-nucleon (Amaldi, 1977, Carroll, 1976; CERN, 1976) and nucleon-nucleus total cross sections (Murthy, 1975) the existing data on nucleon-nucleus inelastic cross sections are from lower energy and of limited precision (Denisov, 1973, Belletini, 1966). The results of the experiment described below should improve this situation.

2. Method The neutron beam produced at about 1 mr by 400 GeV protons striking a 10 cm Be target was collimated to about 1 x 1 mm² and swept of charged particles and gamma rays by various magnets plus lead radiators. The spectrum peaked at about 300 GeV (depending on the exact production angle) with a FWHM of less than 200 GeV. A calorimeter (described previously, Jones, 1974) detected the neutrons whether or not they interacted in a target. The targets were mounted in a holder permitting them to be placed in or out of the beam on alternate beam pulses. A single scintillation counter 10 x 10 cm² (labelled "B"), nominally 8 cm behind the target midplane, served to detect produced charged secondaries, i.e. interactions, in the target. An upstream monitor telescope completed the system. Eight discriminator levels served to record the calorimeter counts according to each of 8 integral pulse height or energy thresholds, C_i.

Cross sections could be calculated in either of two ways: using the B counter to record an interaction in coincidence with a pulse in the calorimeter from which σ_I (for interaction) could be found, or using B

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in anticoincidence and comparing calorimeter counts with the target in and out from which σ_A (for absorbed) could be found. The two cross sections should be the same and indeed they were. In both methods charged particles in the beam and backscatter from the calorimeter should not affect the neutron cross section. In practice, the backscatter was about 1% (for this geometry) and the charged hadron fraction in the beam, less than 0.1%, was so small that it was only increased by the thinnest anti-coincidence counter. The targets were ~ 50 cm ahead of the calorimeter.

The cross section actually measured was that cross section for neutrons producing charged secondary particles which counted in B. The total cross section can be written as:

$$\sigma_T = \sigma_E + \sigma_N + \sigma_I$$

where σ_E is elastic scattering wherein the entire nucleus recoils, σ_N is scattering wherein the nucleus is excited or fragmented but where no mesons are produced (often referred to as quasielastic scattering), and σ_I is the inelastic scattering, including diffraction dissociation of the incident neutron or target nucleons and all other processes leading to meson production. This experiment measures all σ_I processes wherein charged particles are produced. Processes leading to only neutrals (π^o, K^o, n final states) would not be detected efficiently with thin, low Z targets. An attempt was made to detect such processes by preceeding the counter B with a lead converter of 1.2 r.ℓ. (to convert π^o γs) using a thin C target. No effect was observed at the 1% level. The nuclear fragments from the σ_N processes are mostly neutrons, slow protons, and lower-energy βs and γs. Few, if any of these would be detected in this geometry unless exceptionally thin targets were used. In fact efforts to observe such processes by varying the target thickness were unsuccessful, and we conclude that our efficiency for detecting σ_N is negligible.

We have searched for other systematic biases by varying the target-B counter separation, the B-counter signal level, the target-calorimeter separation, beam rate, and the effect of anticoincidence counters as well as target thickness and various sizes, thicknesses, and lead converter configurations for the B-counter. We are satisfied that no biases to our cross section are observable at the 1% level.

Below about 150 GeV there is a small K^o contamination. This was evaluated by placing graphite filters in the beam of up to 150 cm length and measuring spectra and cross sections with three separate lengths of graphite. This data is still being analyzed, and precludes firm statements on cross sections below 150 GeV and softens our possible conclusions on the energy behaviour above 150 GeV.

3. Results Table 1 lists the preliminary results of the cross section measurements averaged over the energy range 150-350 GeV.

Table 1

Inelastic Neutron-Nucleus Cross Sections 150-350 GeV*

Be	195 mb	Cu	783 mb
C	233	Cd	1180
Al	420	W	1700
Fe	713	Pb	1800

*Errors are ± 2% at present.

The 2% errors will be reduced by the analysis and the K^o-correction. Data also exist for deuterium, hydrogen, O, Ta, and U targets.

An effort was made to detect any rise in cross sections over this energy interval (150-350 GeV). This cross section rise is at most 3% (light elements) to 1% (heavy elements), but might be less, as a kaon contamination at lower energies would reduce the apparent cross section at those energies.

4. Discussion and Conclusions These data represent the first direct data relevant to attenuation and interaction of cosmic ray nucleons of over 100 GeV in matter. When fully analyzed, they should permit a detailed analysis of the validity of nuclear structure models and consequently of predictions of the nucleon-nucleon total cross section behaviour based on cosmic ray attenuation measurements.

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